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CHAPTER 1. INTRODUCTION

Nuclear Physics in a Microscopic Approach.

"Why do nucleons behave like nucleons inside nuclei and not like peas in a meson soup?"¹⁾ (G.E. Brown)

Many properties of finite nuclei are described by effective potentials. The nuclear shell-model provides a good example. It is a very successful description of nuclear structure, based on the idea that the nucleon in a nucleus moves in a single-particle potential arising from its interaction with all the other nucleons. By comparing shell-model predictions with experimental nuclear spectra, this single-particle potential can be determined phenomenologically. Although such a procedure has proved its reliability in many practical applications, the goal remains to derive the effective interaction microscopically from the fundamental nucleon-nucleon (NN) interaction. Such a microscopic approach usually proceeds as follows. The free two-nucleon potential is determined from NN-scattering data together with the properties of the deuteron. The properties of the lightest nuclei (^3H and ^3He) and of nuclear matter, predicted by specific NN-potential models are also of interest. For the three-nucleon system these may be calculated using the Faddeev equation. At the other extreme, nuclear matter is the hypothetical extrapolation of the finite nucleus to infinite matter at the observed saturation density, with equal number of neutrons and protons (for which the charge is assumed to be turned off). The binding energy of nuclear matter is given by the volume term in the semi-empirical nuclear mass formula, $E_B = -16 \pm 1$ MeV. From electron scattering data for heavy nuclei it appears that the central density is constant ($\rho = 0.16 \text{ fm}^{-3}$) over a wide range of nuclei. The object of the exercise is to determine to what extent the model of the two-nucleon potential can predict these saturation properties. The advantage that nuclear matter offers, is the very considerable simplification resulting from working with plane-wave nucleon states. As a final step, the model that has proved its success in the two-nucleon system and in the infinite nuclear

matter, can be applied to finite nuclei, either to study nuclear structure properties or for example proton-nucleus scattering.

In many non-relativistic models the two-nucleon interaction is phenomenologically determined from NN-scattering results. However the long range attractive part of the interaction is understood in terms of the Yukawa theory of the exchange of a single pion. The Reid-Soft-Core potential⁴⁾, widely employed in the seventies, provides an example of such a phenomenological NN-interaction containing the one-pion-exchange(OPE) long-range term. One of its successors, the Paris potential⁵⁾ includes the effect of two-pion-exchange, evaluated in a dispersion model. This mechanism is responsible for the medium range attraction of the NN-force. Here too the short-range repulsive part of the interaction is described phenomenologically.

The strong nature of the potential, and in particular its very repulsive core, necessitate approaching the problem (even in the relatively simple case of nuclear matter) in a non-perturbative self-consistent framework. The most widely used has been the Brueckner-Bethe-Goldstone model⁶⁾ which emphasizes a particular summation to all orders of selected diagrams in many-body perturbation theory. Its predictions agree with those obtained in recent variational calculations⁷⁾. A nice status report on these both approaches has recently been given by Jackson⁸⁾. Neither approach has succeeded in reproducing the saturation properties of nuclear matter. Depending on the phenomenological potential chosen one finds binding energies per particle varying from 8 MeV to about 22 MeV at densities, expressed in terms of the fermi momentum k_F ($\rho = 2k_F/3\pi^2$), between $k_F = 1.1 \text{ fm}^{-1}$ and 2.0 fm^{-1} . All the saturation points so obtained lie on a narrow band. Moreover this so-called Coester-line lies far from the empirical point. Coester showed⁹⁾ that the observed discrepancies in the saturation points did not originate from differences in the NN-phaseshift description, but is primarily determined by the strength of the tensor part of the NN-interaction.

In this sense the Brueckner scheme may be regarded as only partially successful. (This remark also applies to the variational approaches based on purely two-nucleon potentials). Qualitatively, however, it contains two important ingredients in our understanding of the nuclear many-body problem. The first is that the effect of the nuclear medium on a specific nucleon can be described by a single-particle potential, which can be self-consistently

determined from the two-nucleon interaction. The second is that it takes into account the effect of the Pauli principle when describing nucleon-nucleon scattering within the nuclear medium, whereby intermediate scattering states may be "blocked" by the presence of other nucleons of the medium in these states.

Moreover it is now realized that certain features of the nuclear problem can only be described by going beyond the non-relativistic semi-phenomenological approach sketched above. In the first place there is the effect of the meson exchange currents. There exist by now clear indications that charged exchanged virtual mesons, which are the quanta of the nucleon-nucleon force, influence the electromagnetic response of the nucleus¹⁰⁾. Secondly, in electromagnetic as well as in pionic reactions the importance of virtual nucleonic isobar states has been confirmed^{11,12)}. Many nucleonic isobars are observed, of which the most important is the $\Delta(3/2^+, 3/2)$. It is the lowest in mass ($m_\Delta = 1.23 \text{ GeV}/c^2$) and is seen as a strong resonance in πN -scattering. These isobars are conveniently explained in a quark model, where the nucleon comprises three quarks in the ground state, and the isobars are excited states of this three-quark system. The Δ -isobar is thought to play an essential role in π -nucleus reactions and in pion production. In nuclear matter, inclusion of the Δ -states offers a possible way to incorporate certain three-body forces¹³⁾, (i.e. forces that cannot be obtained by a pairwise summation of the interactions between two isolated nucleons). These three-body forces play a very important role in non-relativistic nuclear matter theory⁸⁾. Since the two-body forces were not able to reproduce the correct saturation, it was postulated that density-dependent three-body forces might remedy the observed discrepancy¹⁴⁾. At the phenomenological level such three-body terms were shown capable of giving the empirical saturation point of nuclear matter.

The behaviour of nuclear matter far from its saturation point has become a subject of great interest in the fields of relativistic heavy-ion physics and astrophysics, in particular the properties of nuclei in highly compressed and heated states. In the case of astrophysics for example the equation of state of neutron-rich nuclear matter is the basic ingredient for the study of the dynamics of supernova and the formation of neutron stars. It is obvious that phenomenological non-relativistic many-body theories cannot be applied in these highly relativistic regimes.

The last fifteen years have witnessed extended efforts to develop a field-theoretical description of the nucleon-nucleon interaction and its application to the nuclear many-body problem, including mesonic and isobaric degrees of freedom. In such a relativistic field-theoretical framework the NN-force is entirely described by the exchange of mesons. A recent review of this approach has been given by Machleidt¹⁵⁾. By the seventies all low-energy NN-phaseshifts were reproduced by a fully covariant one-meson-exchange model in momentum space (or in coordinate space¹⁶⁾). Many extensions of this model have been studied. We mention in particular the work of the Bonn group, whose potential includes the One-Boson-Exchange diagrams, correlated multi-meson-exchange contributions, and contributions from virtual Δ -states¹⁷⁾. The influence of the Δ -states on the nucleon-nucleon interaction has been studied by many others, most recently by Van Faassen and Tjon¹⁸⁾. In their NN- Δ coupled-channel approach, all NN-scattering observables are calculated up to 1 GeV in the lab. frame. Very reasonable agreement was found. Also particular features in medium energy NN-scattering, which one was forced to ignore in previous OBE-models, like pseudo-resonance structures in several phase shifts and of course the inelasticities, were better reproduced after inclusion of the Δ -isobar.

With respect to the nuclear many-body problem it was known since 1956 from the work of Duerr¹⁹⁾ that nuclear saturation and many properties of finite nuclei could be described by means of a scalar and vector meson field theory. This idea has been applied by many authors to both nuclear matter and finite nuclei. A short historical review can be found in the recent article by Serot and Walecka²⁰⁾. The mean field theory of Walecka is also based on a (renormalizable) model of vector and scalar mesons. Walecka and coworkers emphasize strongly the importance of renormalizability, since in meson field theory, due to the strong couplings constants, one determines only the renormalized coupling constants, either in the vacuum or in a many-body system. In the end the values that Walecka obtained for the meson-parameters in his study on high density nuclear matter were not too different from the corresponding parameters in OBE NN-models.

Miller and Green²¹⁾ and later Brockman and Weise²²⁾ demonstrated that a relativistic Hartree-Fock model based on an OBE-potential could provide a reasonable description of the properties of spherical nuclei. Relativistic

Hartree-Fock calculations have also been applied to nuclear and neutron matter by Horowitz and Serot²³⁾. They furthermore extended the sigma-omega model to a relativistic Brueckner approach. Shortly before, a similar calculation had been performed by Shakin and collaborators²⁴⁾, who used a vacuum OBE interaction to calculate in a Brueckner scheme (however not fully self-consistently) the two-nucleon correlations inside nuclear matter. These calculations were later refined by Brockmann and Machleidt²⁵⁾.

The relativistic many-body approaches establish the importance of the treatment of a nucleon inside a nuclear medium as an effective Dirac particle, where the influence of the coupling of all the surrounding nucleons is expressed by an single-particle interaction or a self-energy, which has a Lorentz structure with large scalar and vector components (with a magnitude in the order of hundreds of MeV) with opposite sign and thus partially cancelling. The use of dressed Dirac wave functions in such relativistic Brueckner schemes provides a new saturation mechanism for nuclear matter, in better agreement with the empirical saturation point than their non-relativistic predecessors. The idea of a single-particle interaction with a Lorentz structure has also been applied to proton-nucleus scattering at intermediate energies. The successful description of the spin properties of these reactions has stimulated the study of the importance of relativistic approaches to nuclear physics. However, the question whether such relativistic approaches are necessary for describing proton-nucleus scattering, i.e. whether a more sophisticated non-relativistic approach might not be equally good has recently been raised²⁶⁾.

In this thesis two subjects of interest are combined: the role of the Δ -isobar in a nuclear medium together with the behaviour of nuclear matter far from saturation, particularly at high densities and temperatures. These interests led us inevitably to a relativistic field-theoretical approach. In the remainder of this introduction we will briefly discuss the main line that is followed in the successive chapters. A more extensive introduction to the different subjects is given at the beginning of each chapter.

To study the influence of Δ -states in nuclear matter a comparison has been made between a purely nucleonic model and a model that contains Δ -degrees of freedom. The free two-body OBE interactions are determined in chapter 2. The reduced coupled-channel Bethe-Salpeter equation that is applied in this

chapter is very similar to the quasi-potential limit of the work of Van Faassen and Tjon¹⁸⁾. In general, relativistic field theory treats particles and anti-particles on the same footing. We shall however restrict ourselves to the positive-energy baryonic states. This approximation turns out to be very reliable, in NN-scattering as well as in the nuclear many-body system. The effect of anti-particle states on the NN-interaction seems to be very small, as was already suggested by the applicability of any non-relativistic theory. Our resulting vacuum model can easily be related to a covariant extension of a Lippmann-Schwinger equation. In chapter 2 we examine the dynamical origin of the decay-width of the Δ . This decay-width is directly related to a self-energy contribution to the Δ -state that originates from the virtual coupling of a bare Δ to its decay-channel. This is studied in detail, because in nuclear matter this self-energy could be significantly affected and thereby altering the influence of the Δ compared to the vacuum case.

Following the systematic procedure that was sketched at the very beginning of this introduction, in chapter 3 we apply the two-body potential determined by us to the system of infinite nuclear matter. The relativistic Dirac-Brueckner (DB) approach that we use can be seen as a very natural extension of the vacuum Bethe-Salpeter equation. The full model, incorporating the Δ -degrees of freedom is of course more elaborate. The nucleonic part of the model will turn out to be very simple and appealing. It combines an accurate description of low-energy NN-phase shifts with an adequate reproduction of the nuclear matter saturation properties. It can therefore be assumed to provide an appropriate starting point for the study of nuclear matter far from saturation. In fact, the full model confirms the reliability of such an approach. The inclusion of Δ degrees of freedom does not change the essential features of the DB-model, in which the Dirac state of the nucleon is strongly influenced by the large self-energy components, resulting in strong enhancement of the lower components of the Dirac spinor.

In chapter 4 we use the same approach to calculate the single-particle interaction of a nucleon with an energy above the nuclear-matter Fermi surface. The calculated self-energies can be related to a non-relativistic optical potential. We emphasize the medium effects on the nucleon self-energy. In our relativistic treatment it appears that the medium effects are important, therefore putting into question the applicability of the

Relativistic Impulse Approximation (RIA) in this energy regime. In some respect this thesis can be seen as a status report. The natural extension of the study of the single-particle interaction to such higher energies where the effect of the Δ may be expected to manifest itself, will be performed in the near future.

Hot and dense nuclear matter will be studied in chapter 5. As we previously stated there is a considerable interest in the equation of state on the part of those engaged in relativistic heavy-ion physics and in astrophysics. We shall present thermodynamical properties of nuclear matter, but also the temperature dependence of the single-particle potential of a nucleon in nuclear matter. Temperature is included in our model by means of the finite-temperature Green's function formalism for the nucleons. It turns out that the resulting set of Brueckner-like equations remains very similar to the $T=0$ case.

The final chapter will present conclusions drawn from this work and suggest directions that further investigations might take.

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